Coloration quenching of radiochromic films irradiated with proton energies close to maximum energy loss *

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Radio**C**hromic **F**ilms (RCF) are widely used as beam diagnostics in the context of laser driven proton acceleration, where typically angular divergent beams (up to 25° half opening angle) with broad exponential energy spectra are generated. RCFs provide a precise measurement of the spatial beam profile and allow to determine the angular distribution. Moreover, used in a so called "stacked" configuration, where several RCFs are staggered behind each other, enables to fully reconstruct the spectral properties of the proton beam. This can be combined with special structured laser-targets to additionally reconstruct important beam parameters like proton source size and transverse and longitudinal beam emittance. The methods to fully characterize laser-accelerated proton beams were earlier published by our group as the so called **R**adiochromic film **I**maging **S**pectroscopy (RIS) [1].

In the scope of the ongoing research to further optimize the RIS, we have focused the attention to the response function of the active layer of different RCF types. Therefore, we have carried out precise dose calibrations with 10 MeV protons from the TANDEM accelerator at the Helmholtz-Zentrum Dresden-Rossendorf to reduce the uncertainty in deposited dose to be less than 5%. Besides this, we have implemented a multi-color-channel calibration [2] which handles each digitized RGB-channel independently. A dynamic range weighting allows to choose the optimum ratio of each calibration to calculate a weighted mean dose from the three color-values. This method extends the dose range of the RCF by a factor of four while at the same time increases the calibration precision over the whole dose range. Furthermore, we have investigated in detail the dose-response function if irradiated by proton energies close to their maximum energy deposition inside the active layer. The maximum energy deposition integrated over the thickness of the active layer material gets reached, if a proton with certain energy gets fully stopped at the end of the active layer material. Therefore, we carried out measurements to scan the proton energy around its maximum energy deposition and investigated its influence on the response function of the RCF. We used complementary scanning methods to vary the proton energy in front of the active layer, either by reducing the proton energy of the accelerator (direct scan) or by using stacked RCFs with aluminum foils of different thicknesses in front. The direct scan was additionally carried out for two different beam currents. To model our experiment we have used the GEANT4 toolkit [3] to simulate the energy deposition inside the active layer material of HD-V2 RCFs. We numerically investigated a parameter study for different proton input energies used in the experiment. It was found that the coloration of films irradiated close to the maximum energy loss is significantly reduced, resulting in a lower dose estimation from our calibration compared to the simulated deposited dose of GEANT4. The relative effectiveness η_{eff} (ratio of measured to simulated dose) of the response function is shown in figure 1. It can be clearly seen that the effectiveness follows a Bragg-curve like slope with its minimum of $(60.5 \pm 0.3)\%$ for input energies of (487 ± 22) keV which corresponds to the input energy of maximum integrated energy loss in the active layer. To fit the data-set (light-blue, 2σ confidence black-dashed) a parameterized Bragg-model was applied. In order to deconvolve our results from the layer thickness we have developed a proton tracking routine based on the SRIM tables. It was embedded inside a least-square fitting routine. The model to deconvolve from layer thickness is derived from the derivative of the parameterized Bragg-model (self-similar ansatz) used before and optimized during the tracking. With this approach we were able to construct a relative differential effectiveness $d\eta_{\text{eff}}/dx$ which can be applied to any MonteCarlo or tracking routine to calculate the response function of RCFs from the differential energy loss including the quenching correction.

Applied to laser-accelerated proton beams, the undervalue in calculated particle numbers will be approx. 20% if the effectiveness of the RCF is not taken into account.

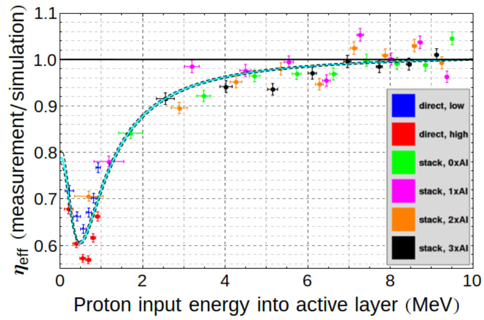

Figure 1: Relative effectiveness of RCF response function for different proton energies into active layer of HD-V2.

References

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* This work is supported by **HIC4FAIR**.